

On the magnetic accretor GK Persei in outburst

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ABSTRACT

RXTE made 5 X-ray observations of the magnetic accretor GK Per during its 1996 outburst, recording a count rate of ten times the quiescent level. The 351-s spin pulse shows a deep, nearly sinusoidal modulation, in contrast to the weaker, double-humped profile of quiescence. The spectrum shows absorption increased by two orders of magnitude over quiescence. We explain these differences in terms of the changing accretion geometry as the outbursting disc forces the magnetosphere inwards, and discuss the 5000-s X-ray QPOs seen during GK Per’s outbursts.

Key words: accretion, accretion discs – stars: individual: GK Per – novae, cataclysmic variables – binaries: close – X-rays: stars.

1 INTRODUCTION

The dwarf-nova outbursts of cataclysmic variables are thought to be caused by accretion-disc instabilities (e.g. Osaki 1996; Lasota 2001). In principle, such outbursts can still occur when the inner disc is truncated by the magnetic field of the white dwarf, as in the intermediate polar subclass (e.g. Angelini & Verbunt 1989). GK Per is an exemplar of this: its long, 2-d orbit and short, 351-s, white-dwarf spin period lead to a large disc surrounding a relatively small magnetosphere. Its outbursts, which last for ≈ 50 d and recur every ≈ 3 y (Simon 2002), can thus be modelled using a disc-instability code with the inner disc missing (Kim, Wheeler & Mineshige 1992; Yi et al. 1992).

Outbursts in some other intermediate polars may also be the result of disc instabilities, for example in XY Ari (Hellier, Mukai & Beardmore 1997), YY Dra (Szkody et al. 2002), HT Cam (Ishioaka et al. 2002), and possibly EX Hya (Hellier et al. 2000). It is likely, though, that short-lived, low-amplitude ‘flares’ seen in TV Col and V1223 Sgr are caused by something else, such as mass-transfer events (Hellier & Buckley 1993).

Of the above systems, X-ray observations in outburst have been obtained for GK Per, XY Ari, YY Dra and EX Hya. Outburst observations of GK Per include *EXOSAT* coverage of its 1983 outburst (Watson, King & Osborne 1985), *Ginga* coverage of its 1989 outburst (Ishida et al. 1992), *RXTE* coverage of its 1996 outburst, and, most recently, *Chandra*, *XMM-Newton* and *RXTE* coverage of the 2002 outburst (Mauche 2003).

We report here on the *RXTE* observations of the 1996 outburst. In particular we address the issue of why the 351-s pulsation is strong and single-peaked in outburst (Watson et al. 1985) but much weaker and double-peaked in quiescence (Norton, Watson & King 1988; Ishida et al. 1992).

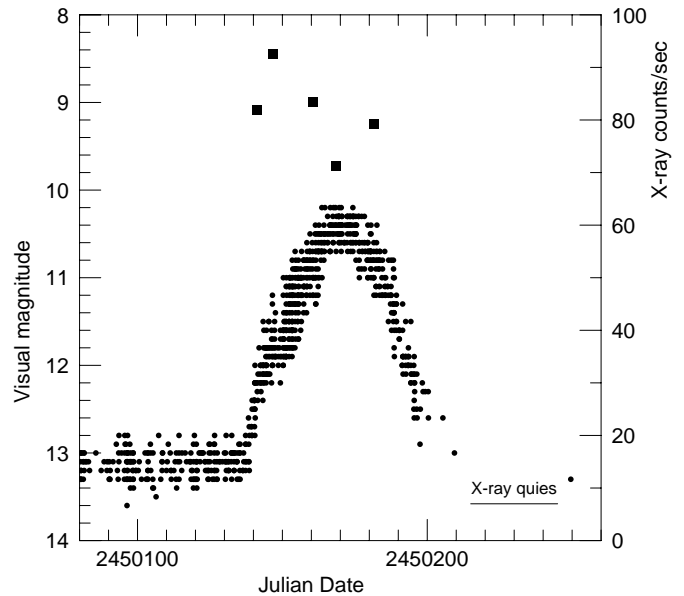


Figure 1. The visual lightcurve of the 1996 outburst (circles), compiled by the AAVSO (Mattei 2003). Also shown are the times and count rates of the 5 *RXTE* observations (squares); the line marks the expected *RXTE* count rate in quiescence, predicted from the quiescent *Ginga* count rate.

2 OBSERVATIONS AND RESULTS

RXTE made five observations of the 1996 outburst of GK Per, lasting ≈ 9 h each, spaced over 41 d (see Fig. 1). We make use of the PCA data extracted from the top xenon layer of PCUs 0, 1 & 2 in the energy range 2–15 keV, and with the background estimated using PCABACKEST v2.1e.

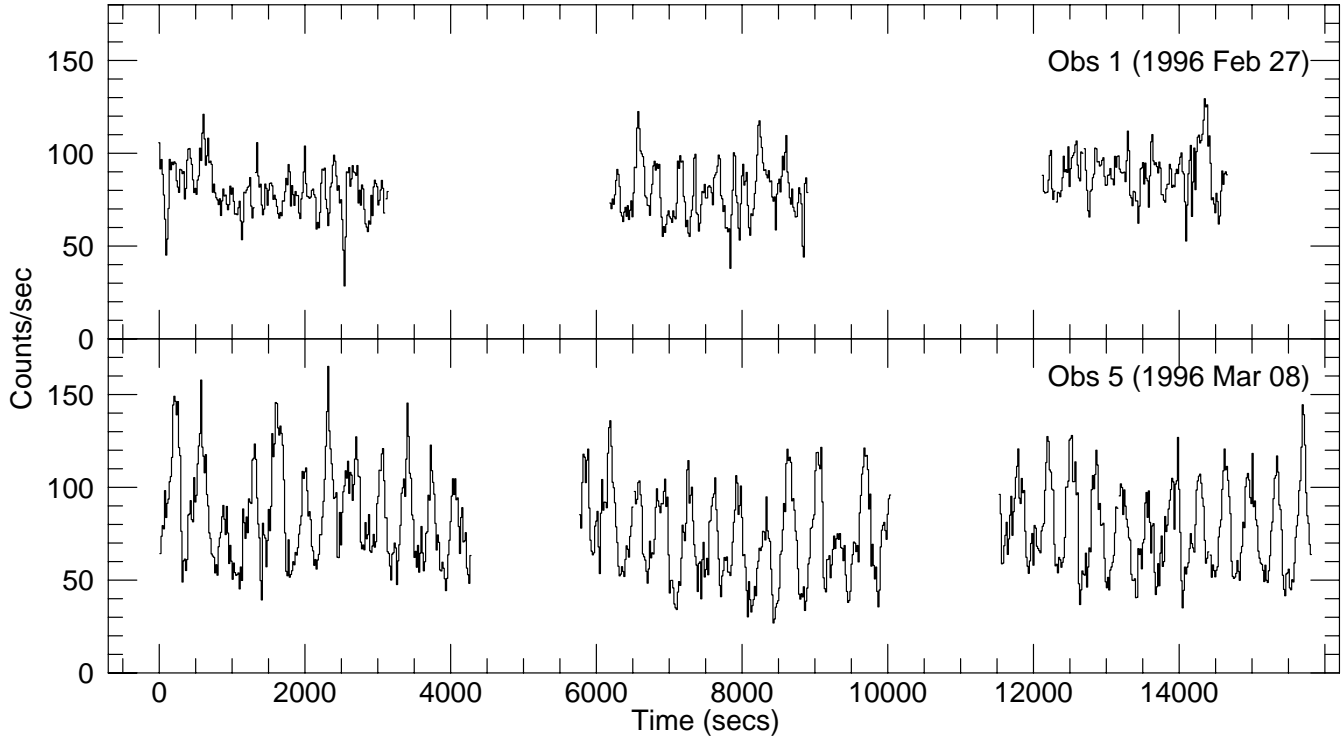


Figure 2. Two samples of the 2–15-keV X-ray lightcurve of GK Per during outburst, in 16-s bins. Errors are typically 3 counts s^{−1}. Time zero corresponds to JD(TDB) 2450140.9392 (top panel) and 2450181.6800 (lower panel).

The mean 2–15-keV flux in the 5 observations was $50 \pm 8 \times 10^{-11}$ ergs s^{−1} cm^{−2}; for comparison, Ishida et al. (1992) report that in *Ginga* observations of the 1989 outburst the 2–20-keV flux was $48 \pm 17 \times 10^{-11}$ while the quiescent flux is much lower at $4.0 \pm 0.4 \times 10^{-11}$ ergs s^{−1} cm^{−2}.

We show in Fig. 2 sections of lightcurve from the 1st and 5th observations. The 5th observation shows the single-peaked, quasi-sinusoidal modulation that is typical of intermediate polars. In contrast, the first observation shows a shallower, flat-topped modulation that is similar to the quiescent pulse recorded by Ishida et al. (1992), despite the count rate being already well above the quiescent level.

For further comparison we plot the folded pulse profiles of all 5 observations in Fig. 3, and their 6–10/2–5-keV hardness ratios in Fig. 4. Note that observations 3 and 4, nearest the peak of the outburst, have the highest hardness ratios. This can be seen from Fig. 4 where these observations are displaced upwards from equal spacing. Spectral analysis confirms that all the outburst spectra are heavily absorbed, requiring at least two partial-covering absorbers of densities $\approx 3 \times 10^{23}$ cm^{−2} and $\approx 2 \times 10^{24}$ cm^{−2}. This was also reported by Ishida et al. (1992) during the 1989 outburst, and contrasts with typical quiescent absorption of only $\approx 1 \times 10^{22}$ cm^{−2}.

Intermediate polar spectra typically show increased hardness in the minima of the spin pulses, owing to increased absorption, and this is seen in observations 2 to 5. In contrast, the first observation shows a more complex and shallower spectral change.

We have used the last 4 observations, which span 35 d, to measure the pulsation period (the first was omitted owing

to the different pulse shape). From these we find a period of 351.335 ± 0.002 s, where the error makes no allowance for possible changes in pulse profile. This result is in line with Mauche’s (2003) re-assessment of GK Per’s period change over that originally proposed by Patterson (1991).

3 THE 5000-S QPOS

In the *EXOSAT* observations of the 1983 outburst Watson et al. (1985) reported modulations of the X-ray flux which had a strong amplitude of up to a factor 2–3, and a quasi-periodic timescale of ~ 5000 s. Hellier & Livio (1994) proposed that they were caused by bulges in the inner disc, orbiting with the local Keplerian timescale of 5000 s, as might arise from an overflowing stream reimpacting the disc. These bulges would periodically obscure the line of sight to the X-ray emission, causing absorption dips. The dips are deeper at lower energies, in keeping with this idea.

Morales-Rueda, Still & Roche (1999) analysed optical spectroscopy of the 1996 outburst and found the same 5000-s QPOs in the emission-line profiles. They proposed an alternative model in which blobs at the inner disc edge orbit with a period of either 320 or 380 s. These would cause enhanced flow to the accretion curtains and hence enhanced absorption whenever a blob lined up with the magnetic dipole, thus producing a modulation at the 5000-s beat period between the blob orbits and the 351-s spin period.

While this idea adequately explains the optical data analysed by Morales-Rueda et al. (1999), it is less able to explain the X-ray behaviour. For example, the extra absorption would not occur when the blob-fed curtain was on the

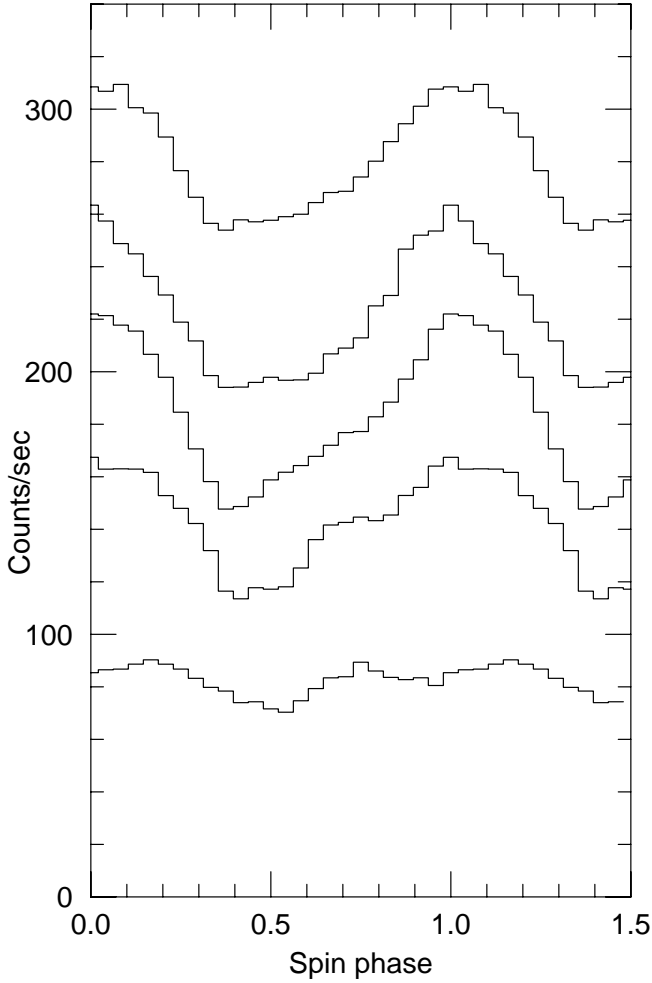


Figure 3. The spin-pulse profiles from the 1st (bottom) to 5th (top) X-ray observations. We have added 50 counts s^{-1} successively to the upper 4 profiles. Photon-noise error bars are typically 0.5 counts s^{-1} . The data are folded on a period of 351.335 s with phase zero corresponding to JD(TDB) 2450168.14105.

far side of the white dwarf, as it would be for half of each spin cycle. Indeed, one might expect the extra accretion flow of a blob-fed curtain to result in enhanced flux for these spin phases. The observations, though, show that the extra absorption of the QPO occurs throughout the spin cycle, reducing the flux at all spin phases (see Watson et al. 1985 and Hellier & Livio 1994). For this reason we prefer models in which the structures causing the dips are circling at the 5000-s quasi-periodicity.

More recently, Warner & Woudt (2002) have proposed a new understanding of the QPOs and dwarf-nova oscillations (DNOs) seen in cataclysmic variables. They associate DNOs with a magnetospheric rotation period and suggest that QPOs are caused by slow-moving prograde waves at the inner edge of the disc. Warner, Woudt & Pretorius (2003) show that a relation $P_{\text{QPO}}/P_{\text{spin}} \approx 15$ fits many observations in cataclysmic variables and X-ray binaries; GK Per obeys this relation with $P_{\text{QPO}}/P_{\text{spin}} \approx 5000/351 \approx 14$.

Given this, we retain Hellier & Livio's (1994) proposal that GK Per's QPOs are dipping behaviour caused by bulges moving at ~ 5000 s, but now regard Warner & Woudt's

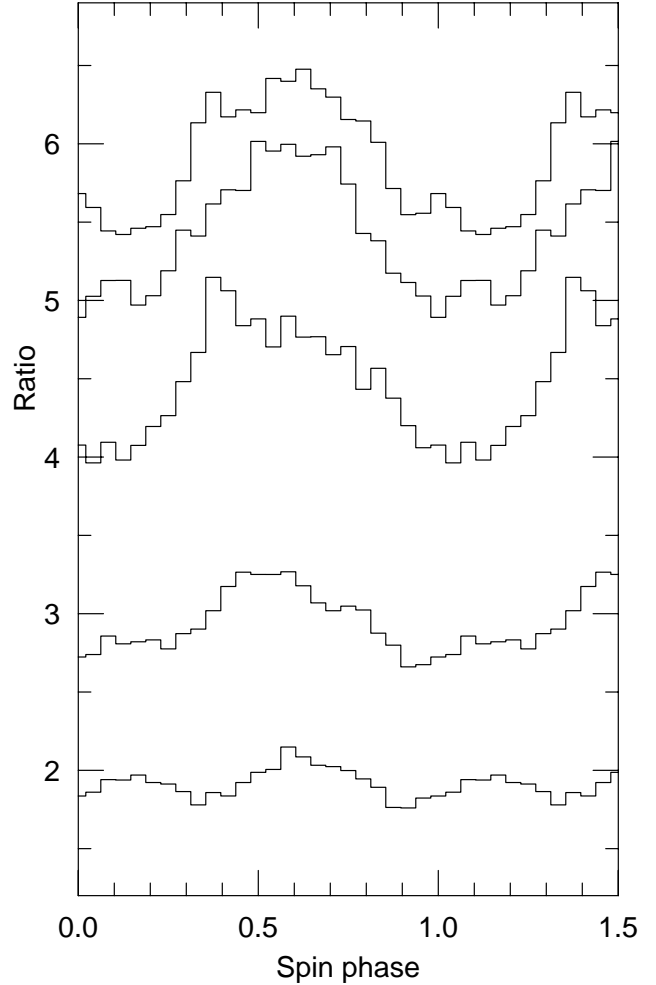


Figure 4. The 6–10/2–5-keV hardness ratios, folded on the spin cycle, from the 5 *RXTE* observations. We have added 0.5 successively to the upper 4 profiles. Photon-noise error bars are always less than 0.1 (typically 0.05). The phase zero is the same as in Fig. 3.

(2002) explanation of the bulges as slow, prograde travelling waves as the most promising.

Morales-Rueda et al. (1999) observed that the emission-line QPOs were predominantly blueshifted, and suggested that this argues against a model in which structure moves at 5000 s. However, it is plausible that the waves have a leading-edge/trailing-edge asymmetry in emissivity, which would explain the Morales-Rueda et al. result.

The relevance to this paper is that optical observations by Morales-Rueda et al. (1999) and Nogami, Kato & Baba (2002) show that the QPOs were present during the 1996 outburst discussed here. (We have attempted to detect them in the *RXTE* data, but the search was inconclusive since the data are broken up by *RXTE*'s orbit on the very similar timescale of 6000 s.) Their existence shows that GK Per has a sufficiently high inclination that, at least during outburst, bulges of material at the inner disc edge are capable of obscuring the line of sight to the white dwarf and reducing the flux by factors of 2–3. This is important for the discussion on the origin of the spin pulse.

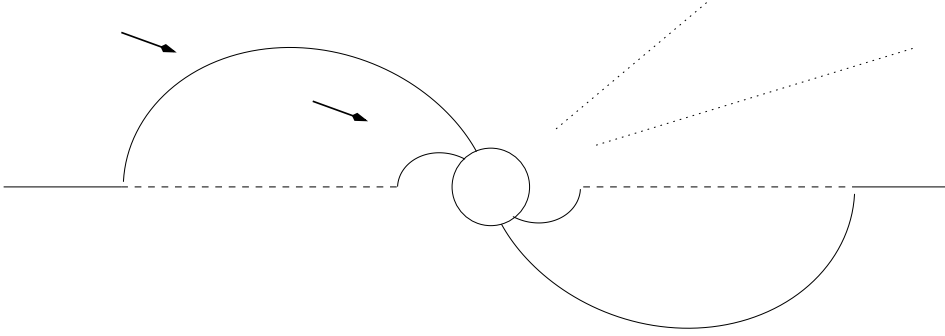


Figure 5. An illustration of the change in accretion geometry during outburst, showing the magnetosphere shrinking markedly as the disc pushes inwards. The dotted lines show the $50\text{--}73^\circ$ allowed inclination range. The arrows show how the line-of-sight through the accretion regions can become more tangential during outburst.

4 COMPARISON WITH XY ARI: HIDING THE LOWER POLE?

Like GK Per, XY Ari shows a low-amplitude, non-sinusoidal pulse in quiescence. This most likely results from minor asymmetries between two accreting poles, so that the disappearance of one as the white dwarf spins is not entirely balanced by the appearance of the other.

In outburst, XY Ari's pulse changed to a very deep, quasi-sinusoidal modulation. The minima were not accompanied by increased hardness suggesting that absorption played no role. Noting that XY Ari was deeply eclipsing and thus at a very high inclination, Hellier et al. (1997), suggested that the inner disc had pushed inwards during outburst, cutting off the line of sight to the lower accreting pole. Thus we saw only the upper pole, and this passed from the visible face to the far side and back as the white dwarf rotated, producing a near-total modulation.

GK Per's pulse also changes from low-amplitude and non-sinusoidal in quiescence to deep and sinusoidal in outburst (Fig. 3). It is thus natural to ask whether the same effect is occurring. An immediate counter is that, unlike in XY Ari, GK Per's outburst pulse is energy dependent and caused primarily by an increase in absorption at spin minimum. Thus the model cannot apply straightforwardly.

Nevertheless, let us consider whether the system parameters are compatible with hiding the lower pole in outburst. We assume a $1\text{-}M_\odot$ white dwarf (see Morales-Rueda et al. 2002), which, with a 351-s spin pulse, produces a magnetosphere of $\approx 10 R_{\text{wd}}$, assuming that it corotates with a Keplerian inner disc. There are arguments for a much larger magnetosphere, based on spectra and modelling the outbursts (e.g. Kim et al. 1992), but the presence of pulsed X-rays in quiescence implies that accretion is not centrifugally prohibited, so we place the inner disc edge at the corotation radius.

A linear scaling with optical and X-ray brightness would suggest that the accretion rate rises by a factor ≈ 10 during outburst. However, this is not in accord with disc-instability models of the outburst, and Kim et al. (1992) and Yi et al. (1992) argue that the accretion rate rises by a factor $\sim 100\text{--}1000$, with the X-rays being suppressed by opacity. The standard scaling of disc radius with accretion rate ($r \propto \dot{m}^{-2/7}$) then implies that the inner disc radius decreases by a factor

of between 4 and 7 (we show an illustrative reduction by a factor 4 in Fig. 5). The system inclination is within the range $50\text{--}73^\circ$ (Morales-Rueda et al. 2002).

The above ranges are not tight enough to tell us whether the bottom of the white dwarf is hidden by the disc in outburst (particularly given the uncertainty in the disc thickness), but allow both possibilities. We thus turn to considering the observations.

The high amplitude of the 5000-s QPOs (reductions in X-ray flux by factors up to 2–3) imply that bulges near the inner-disc edge obscure the upper accretion pole, and are thus of a height above the disc plane comparable to the white-dwarf radius. This is reinforced by the observation of very high absorption (10^{24} cm^{-2}) at all times during outburst. Given the inclination range of $50\text{--}73^\circ$, and the likely inner disc radius of $< 3 R_{\text{wd}}$, such material would likely hide the lower pole continually.

Note, however, that we don't see episodes of near-zero flux each spin cycle, which we do in XY Ari when the upper pole swings round to the hidden face of the white dwarf. This implies either that the lower pole is visible at phases when the upper pole disappears, or that accretion regions at the upper pole are visible at all spin phases. The latter is, at first sight, implausible for the above inclination range. The small magnetosphere during outburst implies accretion regions far from the poles ($> 35^\circ$ magnetic co-latitude for $r_{\text{mag}} < 3 R_{\text{wd}}$), which, added to any dipole offset from the spin axis, will likely exceed the $90^\circ - i$ polecap region that is always visible.

So can we reconcile these conflicting indicators? We suggest that, in outburst, the accretion flow overwhelms the magnetosphere sufficiently that accretion flows to the poles from all azimuths (whereas, in quiescence, each pole would be fed from a restricted azimuthal range), and thus falls at all magnetic longitudes. Hence accretion at the upper pole would always be visible. There is evidence from eclipse timings that exactly this occurs at the peak of the outburst in XY Ari (Hellier et al. 1997). If the above is correct, it suggests that the angle between the spin and magnetic axes is relatively small.

5 THE CHANGE IN THE SPIN PULSE

The fact that the pulse profile in GK Per is largely an absorption dip, and not the near-total, energy-independent modulation seen in XY Ari in outburst, implies that simply hiding the lower pole does not explain the change in pulse profile between quiescence and outburst. We are thus left to explain the fact that (1) in outburst GK Per shows a ‘typical’ pulsation with a quasi-sinusoidal profile resulting from a broad absorption dip, and (2) the absorption dip is much reduced in quiescence leaving a more-complex, lower-amplitude modulation.

We suggest that the change results straightforwardly from a combination of three factors. First, the increase in accretion rate by a factor ~ 100 – 1000 will increase the column density of the accretion curtains. Second, the marked shrinking of the accretion curtains in outburst (see Fig. 5) will force the increased flow through a much smaller circumference and thus a much smaller area, further increasing the column density. Third, as illustrated in Fig. 5, the change in geometry can easily result in the line-of-sight to the accretion regions taking a more grazing path through the accretion curtains, thus increasing the line-of-sight column yet further. Such effects can explain why we observe a phase-varying column as high as $2 \times 10^{24} \text{ cm}^{-2}$ in outburst, whereas the quiescent spin pulse is modelled by phase-varying absorption of only $6 \times 10^{21} \text{ cm}^{-2}$ (Ishida et al. 1992).

Thus, in outburst, the effect of intense absorption dominates the pulse profile, whereas in quiescence the much weaker absorption, from tenuous accretion curtains much further from the white dwarf, is less significant than other factors, such as an asymmetry between the two poles.

6 CONCLUSIONS

(1) X-ray QPOs are caused by bulges at the inner disc edge, travelling at a 5000-s period. They likely correspond to the travelling waves discussed by Warner & Woudt (2002). The bulges are at a height above the disc plane comparable to the white-dwarf radius.

(2) We suggest that the X-ray QPOs are not seen in quiescence owing to the inner disc being much further out, so that the bulges do not obscure the white dwarf.

(3) During outburst, accretion occurs from all azimuths, forming a complete accretion ring at the poles. The lower pole is likely hidden.

(4) The pulse profile changes in outburst to become dominated by absorption; this results from the greater accretion flow, the smaller accretion-curtain area, and the change in how the line-of-sight passes through the curtains.

(5) Measurement of the 351-s spin period confirms the period change reported by Mauche (2003).

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